DEPOSITION OF FINE SEDIMENTS IN SIBSTRATES & THEIR EFFECTS ON SURVIVAL OF TROUT EMBRYOS

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# DEPOSITION OF FINE SEDIMENTS IN SUBSTRATES AND THEIR EFFECTS ON SURVIVAL OF TROUT EMBRYOS

by


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## Abstract

A laboratory study was conducted to assess the effects of silt and clay-sized particles on the survival to emergence of trout embryos. Fine sediment <0.25 mm in diameter was added to troughs containing trout embryos incubating in gravel substrate and survival to emergence and development of emergent fry was determined. Artificial redd formations and the presence of sediment particles 0.25-4.75 mm in diameter in the incubation substrate were also tested for their effect on survival and development of the trout embryos. We found that deposition of sediment <0.25 mm diameter was higher, and survival and development of trout fry was lower, as more fine sediment was added to troughs during the test and when particles 0.25-4.75mm were initially present in troughs. We were unable to detect a relationship between redd-shaped substrate surface on embryo-to-emergent fry survival or development. Fry survival declined significantly when fines <0.25 mm diameter in the egg pocket approached 5% of substrate.

## Introduction

This project was undertaken to assess the effects of silt- and clay-sized sediment on the incubation and emergence of salmonid embryos. Tests were conducted in laboratory flumes filled with a selected size range of gravel. Newly-fertilized eggs were placed in the gravel and fine sediment added. Emergence of fry from the gravel was the measure of survival used to evaluate the effect of various concentrations of fine sediment in the substrate.

Fine sediment has been defined as particles <6.35 mm in diameter, coarse sands and smaller particles (Chapman 1988), and <0.833 mm in diameter (Iwamoto et al. 1978; Everest et al. 1987). In granitic batholith watersheds, fine sediment is mostly coarse and fine sands (0.06-2.0 mm diameter) with relatively small amounts of the silt- and clay-sized particles (<0.06 mm diameter). Silts and clays are more abundant in watersheds with loess, sedimentary, and belt series soils.

The quality of habitat used by salmonids for spawning can be degraded by forest practices, farming, grazing, mining, and road construction. Activities that increase erosion in watersheds often result in increased concentrations of fine sediment in stream substrates. Salmonid embryo survival and fry emergence are inversely related to the amount of fine sediment in stream substrates (Tappel and Bjornn 1983; Wetzel and MacCrimmon 1983; Irving and Bjornn 1984; Tagart 1984; Shepard et al. 1985; Young et al. 1991). Fine sediment can decrease the amount of dissolved oxygen available to developing embryos by impeding the flow of water through the substrate and through oxidation of organic material in fine sediment (Coble 1961; McNeil and Ahnell 1964; Bjornn 1969). Low oxygen availability from excess fine sediment has been associated with smaller and less developed emergent fry (Garside 1959; Phillips et al. 1975; Wetzel and MacCrimmon 1981). Hatching delay, premature hatching or lengthening of the hatching period may be induced by reduced oxygen supply (Mason 1969; Wetzel and MacCrimmon 1981; Irving and Bjornn 1984). Decreased water flow through substrate can result in a buildup of nitrogenous wastes. Fine sediment can also block substrate interstices and thereby impede fry emergence (Bams 1969; Hall and Lantz 1969; Phillips et al. 1975; Wetzel and MacCrimmon 1981).

Although many studies have been conducted on the effects of fine sediment on salmonid embryos, application of study results should be limited to watersheds that contain comparable sediment. Studies conducted with granitic sands have little use in evaluating effects of silts and clays on embryos. For example, Bjornn (1969) tested the effects of granitic sands on the emergence of steelhead *Oncorhynchus mykiss* and chinook salmon *O. tshawytscha*. He placed a set mixture of gravel-size particles and granitic sands in laboratory troughs to simulate stream beds and then added embryos that incubated and emerged through the substrate mixtures. A model was developed that could be used to predict effects of granitic sands on embryo incubation and emergence, but that model would not be useful in watersheds where silts and clays were the predominant fine sediment.

The primary goal of this study was to assess the effects of adding inorganic and organic sediment of fine sand, silt and clay particles <0.25 mm in diameter on rainbow trout embryo survival and fry emergence in simulated redds with test substrate mixtures. The accompanying null hypothesis being,

Ho: Additions of fine sediment <0.25 mm diameter will have no effect on survival and emergence of trout fry from incubation substrate.

In a review of sediment related studies, Chapman (1988) stated that researchers conducting sediment studies, especially those performed in laboratories, did not consider the effects of redd characteristics on the relationship between fine sediment and embryo survival. For example, Cooper (1965) demonstrated how the redd pit and tailspill may increase intragravel flows through areas containing egg pockets. Also, female salmonids remove fine sediment from egg pockets and from the surrounding area during spawning, which may improve embryo incubation conditions (Chapman 1988). We tested the effect of gravel cleaning that occurs during spawning on embryo survival by removing sediment particles smaller than 4.75 mm diameter from substrate added to some troughs and by retaining particles 0.25-4.75 mm diameter in other troughs. The effect of redd morphology was tested by comparing embryo survival in troughs with substrate surface formed in the shape of the pit and tailspill of salmonid

redds to survival from troughs with a level substrate surface shape. The null hypothesis for these tests were,

Ho: The removal of sediment particles smaller than 4.75 mm diameter from incubation substrate prior to addition of fertilized trout eggs will have no effect on survival of the trout embryos.

Ho: The presence of a pit and tailspill in the incubation substrate will have no effect on the survival of the trout embryos.

## Methods

This study was conducted in the wet lab at the University of Idaho, Moscow, in 1994. Experiments were conducted in troughs containing selected substrate (river rock) used to simulate incubation conditions for trout embryos. Fine sediment <0.25 mm in diameter was collected from banks of the Palouse River, and was added to selected troughs while trout embryos incubated. Survival of trout to the emerging alevin stage was related to fine sediment accumulated in each trough during the experiments. Three variables tested for their effects on embryo survival and development were shape of the substrate surface (redd morphology versus non-redd level surface), initial substrate size composition, and amount of fine sediment added during a trial (Table 1). Two experimental trials were completed for this study, but usable results were obtained only from the second trial because of a fungal disease that caused excessive embryo mortality during the first experiment. Trial II was conducted during January and February 1994, and lasted 25 days.

### *Experimental Trough System*

Experiments were conducted in a recirculating flume system consisting of 48 troughs (experimental units) connected to a 817 L sump tank (Figure 1). Each trough was 121.9 cm long x 30.5 cm wide x 30.5 cm deep (surface area = 0.37 $m^2$). Water was pumped from the sump tank to each trough and then returned to the sump via gravity feed. Chilled and aerated water was added to the system at a rate of 60.8 L/min

Table 1. Experimental design used for trial, including the three variables of substrate mixture, substrate shape, amount of fine sediment added, and number of replicates per treatment. Truncated = particles 38.1 to 4.75 mm, full-spectrum = particles 38.1 to 0.25 mm.

| Substrate mixture | Substrate shape | Fine sediment added (kg) | Replicates |
|---|---|---|---|
| Truncated | Redd | 0 | 3 |
| Truncated | Redd | 4.5 | 4 |
| Truncated | Redd | 9.0 | 4 |
| Truncated | Redd | 18.0 | 4 |
| Truncated | Non-redd | 0 | 3 |
| Truncated | Non-redd | 4.5 | 4 |
| Truncated | Non-redd | 9.0 | 4 |
| Truncated | Non-redd | 18.0 | 4 |
| Full-spectrum | Non-redd | 0 | 3 |
| Full-spectrum | Non-redd | 4.5 | 4 |
| Full-spectrum | Non-redd | 9.0 | 4 |
| Full-spectrum | Non-redd | 18.0 | 4 |

and excess water was wasted to a floor drain. Two chillers located in the sump tank provided additional temperature control (mean = 12.9°C). Standpipes were used to control water level and gradient within each trough. Flow through the troughs was set to provide a 2% gradient between the inflow and outflow ends of the system. Due to the differences in substrate composition and substrate surface shape, gradient varied between troughs but were maintained as close to the target 2% level as possible. Flow was through the substrate only, until fry began emerging, at which time water was allowed to flow above the substrate. Aluminum screens, with 6.35 mm perforations, were placed at either end of the troughs to contain substrate material. Screens with 1.6 mm perforations were later added upstream and downstream from the first set of screens to contain emerging fry. The trough system was constructed with 19 mm thick plywood, coated with fiberglass resin, and water was conveyed through PVC pipes and valves.

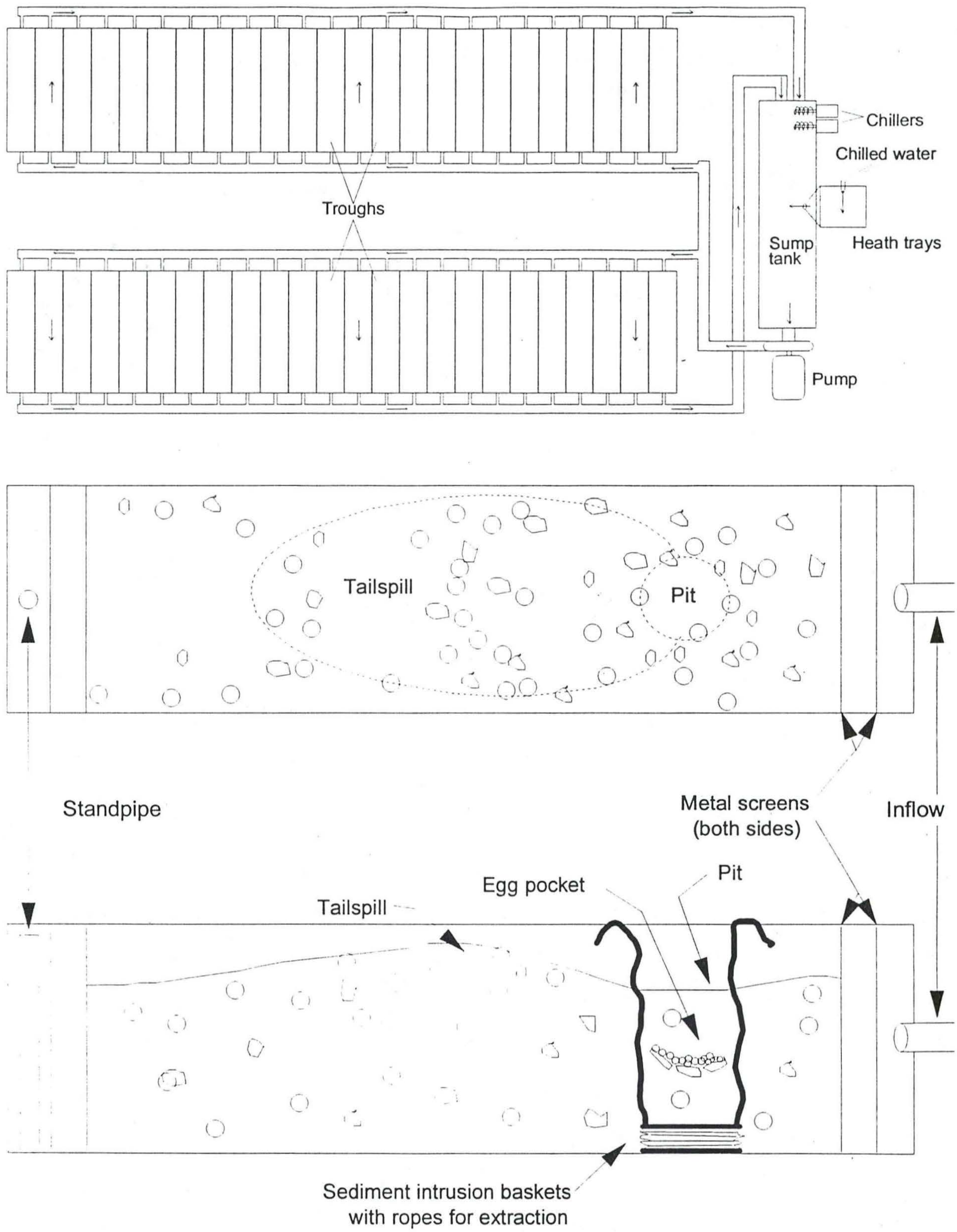


Figure 1. Drawing of recirculating trough system used for conducting sediment experiments, and top and side view of a single trough showing example of simulated redd with egg pocket.

### *Substrate Mixtures*

River rock of controlled size composition was used as substrate material in the troughs. Two particle mixtures were used. We referred to one mixture as truncated because it contained particles from 38.1 to 4.75 mm in diameter. Particles smaller than 4.75 mm were removed. The second mixture also contained particles larger than 4.75 mm plus a pre-determined amount of particles 4.75 mm to 0.25 mm in diameter, to create what we refer to as the full-spectrum mixture (Table 2). The two substrate mixtures were used to assess differences in accumulation of fine sediment with and without small substrate particles initially present.

Two batches of river-run gravel averaging 30.5 mm and 19.0 mm in diameter were used to create substrate mixtures. River-run rock was placed on a 4.75 mm screen and rinsed. Particles less than 4.75 mm that fell through the screen were dried in an oven at approximately 65°C and dry sieved with a mechanical shaker. Particles were separated into size classes with the following sieve mesh sizes: 4.75 mm, 3.35 mm, 2.0 mm, 0.833 mm, 0.5 mm, 0.25 mm, and <0.25 mm. Cleaned and sized rock larger than 4.75 mm was mixed with a shovel and placed in all troughs. Particles 4.75 mm to 0.25 mm in diameter were added to the mixture placed in troughs designated to receive the full-spectrum mixture. Particles were mixed thoroughly with a shovel in individual batches and placed into the troughs. Sub samples were tested by passing through graduated sieves to confirm mixture composition (Table 2).

### *Redd versus Non-Redd Substrate Surface Shape*

Redd morphology and the removal of fine sediment from the egg pocket during spawning may improve the rearing environment for developing embryos (McNeil and Ahnell 1964; Cooper 1965; Young et al. 1989). Effect of egg pockets and surface morphology on fine sediment accumulation was assessed by shaping substrate in 16 of the troughs (randomly assigned) as redds and in the other 32 troughs, substrate material was level with no pit or tailspill. A garden trowel was used to excavate egg pockets and form a pronounced pit and tailspill (Figure 1). Egg pockets were located at the leading (upstream) edge of the tailspill, according to descriptions by Chapman

Table 2. The intended and actual measured percent of river rock retained on sieves of various mesh sizes used for substrate material in troughs with truncated (no particles < 4.75 mm in diameter) and full-spectrum mixtures.

| Sieve mesh size (mm) | Truncated mix (%) | | Full-spectrum mix (%) | |
|---|---|---|---|---|
| | Intended | Actual | Intended | Actual |
| 25.00 | 20.0 | 20.0 | 18.7 | 19.4 |
| 19.00 | 40.0 | 40.0 | 37.4 | 40.0 |
| 12.70 | 18.0 | 18.0 | 16.8 | 16.3 |
| 9.50 | 7.0 | 7.0 | 6.5 | 6.5 |
| 6.35 | 10.0 | 10.0 | 9.3 | 7.7 |
| 4.75 | 4.0 | 4.0 | 3.7 | 2.2 |
| 3.35 | 0 | 0.2 | 2.8 | 2.9 |
| 2.00 | 0 | 0.03 | 1.9 | 2.0 |
| 0.83 | 0 | 0.01 | 1.4 | 1.3 |
| 0.50 | 0 | 0.01 | 0.9 | 1.1 |
| 0.25 | 0 | 0.01 | 0.5 | 0.4 |
| <0.25 | 0 | 0.74 | 0 | 0.2 |

(1988) and Young et al. (1989). Embryos were placed into the bottom of egg pockets through a 2.5 cm diameter PVC pipe and dispersed by moving the PVC pipe back and forth. Substrate material was then moved over the egg pocket to cover embryos. Redd dimensions were restricted by space confines of the troughs. Average depth of egg pockets was 6-8 cm from the substrate surface and redds averaged 1 m long x 0.3 m wide. As a comparison, natural cutthroat trout redds measured by Thurow and King (1994) averaged 1.58 m long x 0.6 m wide. For non-redd (level) substrate shapes, embryos were placed in the bottom of excavated holes in the same location as egg pockets, as described above, but the substrate placed over the embryos was leveled.

### *Embryos*

Gametes were fertilized on site, water-hardened, disinfected, and then placed in the substrate. Hatchery rainbow trout embryos used for this study were donated by Trout Lodge in McMillian, WA. Two-hundred embryos were placed in each trough. Five-hundred embryos were also placed in a Heath Tray incubator as a control to assess embryo viability. Embryos in the Heath Tray incubator used the same water

source as troughs except that the water was flow-through rather than recirculated. Water passed through a packed column for aeration, then into the Heath Tray incubator, and then into the sump to be circulated to the rest of the troughs (Figure 1). Emerging fry were collected from troughs using a small net and were preserved in formalin for at least six weeks for later analysis.

An outbreak of the fungus *Saprolegnia sp.* during the first trial caused significant mortality to the developing embryos and negated the usefulness of data collected from that experiment. During the second trial, embryos were treated daily with formalin to control the fungus. Formalin was added to the inflow to the troughs at 600 ppm for 15 min using reduced, but continuous flow. Formalin solution was applied via gravity feed from a plastic carboy. During formalin treatment, the outflow water was wasted to a floor drain.

### *Fine Sediment Addition*

Four levels of fine sediment (<0.25 mm diameter) were added to troughs: 0, 4.5, 9.0, or 18.0 kg of fine sediment, during an experiment (Table 1). Sediment treatments were chosen to represent potential range of natural exposure to fine sediment and to produce measurable differences in sediment deposition. Fine sediment used in this experiment was excavated from the banks of the South Fork of the Palouse River, a fourth order tributary of the Snake River. The Palouse River contains accumulations of silts and clays from erosion of the surrounding agricultural farmlands. Once the sediment was extracted from the stream, it was dried at 45°C in an oven for approximately 24 h. Dried sediment was powdered with a mechanical grinder. The resulting size distribution of particles less then 0.25 mm in diameter, determined by the hydrometer particle size distribution method, yielded an average of 45% fine sand (0.062-0.25 mm diameter), 45% silt (0.004-0.062 mm diameter) and 10% clay (0.00024-0.004 mm diameter). The silt and clay components (< 0.62 mm) were mixed with a known volume of water in a 50 L plastic carboy and the slurry was then applied to the appropriate trough via gravity feed through a hose. Air pumped through a 30.5 cm air stone placed inside the carboy was used to keep particles in suspension during

application. Sediment was added to a trough over a three day period for each treatment. This method simulated a storm event which rendered the stream turbid for a short duration each day over a three-day period. During the slurry-introduction period, discharge from troughs receiving sediment was diverted to a drain in the floor to reduce deposition of sediment into other troughs not receiving the treatment.

***Sediment Intrusion Baskets***

Collapsible canvas baskets were used to collect the substrate and provide a measure of the amount of fine sediment that had settled into the egg pocket during incubation. A collapsed basket (about 30 cm in diameter) was placed in the bottom of each trough at the site where an egg pocket was to be constructed (Figure 1). Cords attached to the top ring of the basket were left exposed over the side of the trough while substrate was placed in the trough, the egg pocket was constructed, eggs were placed in the pocket and were covered with substrate, and the redd or level surface was shaped. When fry emergence was complete, flow through the trough was shut off, the intrusion baskets were extracted vertically using the cords attached to the top ring, and the contents were dumped into a tray. Any fry, alevins, and embryos were removed. Substrate was dried in a 65°C oven for at least 24 hours and then passed through sieves using a mechanical shaker. Contents of each sieve were weighed to determine the dry weight substrate size distribution for each trough. This procedure was repeated for samples taken with a shovel upstream and downstream from the egg pockets to determine the amount of sediment at locations other than in the egg pocket.

Percent of organic content in the substrate was determined by ashing. Three, 30 g sediment samples were collected from each trough. Sediment was dried at 105°C, weighed to the nearest 0.01 g, ashed at 500 °C, rehydrated with deionized water, dried at 105°C, and weighed a second time. Differences between the first and second weights represented the amount of organic material ashed. The three sample values of organic content were averaged for each trough.

### *Fry Survival and Development*

Data collected consisted of the number of fry emerging from each trough, fry wet length, developmental index (see below), and percentage egg sac remaining. Survival was estimated by comparing the number of fry that emerged from each trough to the number of embryos initially placed in egg pockets. The trial was terminated one week after fry emergence had ceased. Fry found in gravel at the completion of the trial were not enumerated and were not included in the survival estimates. Fry wet lengths were measured using calipers, to the nearest 0.1 mm. Fry wet weights were calculated using a linear regression from measurements of moisture loss during drying (Reiser and White 1981). Fry dry weight condition factor (KDW) and wet weight condition factor (KWW) were calculated using modifications of Fulton's condition factor (Fulton 1911) as follows,

$$KDW = \frac{\text{dry weight (mg)} \times 10^3}{\text{fork length}^3\text{ (mm)}} \qquad [1]$$

$$KWW = \frac{\text{wet weight (mg)} \times 10^2}{\text{fork length}^3\text{ (mm)}} \qquad [2]$$

Developmental index (KD), calculated according to the formula,

$$KD = \frac{\text{Sq. Rt. wet weight (mg)} \times 10^3}{\text{fork length (mm)}} \qquad [3]$$

is a relative measure of condition used to compare emergent fry of varied sizes (Bams 1970). Values larger than 2.0 for emergent fry are an indication that the yolk was not fully absorbed, values near 1.95 indicate yolk absorption completed and values of 1.90 or less indicate fry reabsorbing body tissue at the expense of growth. In this case, a higher KD value would be an indication of slow development by incubating embryos. Percent egg sac remaining was determined from weighing fry and excised yolk sacs on a metler scale to the nearest 0.1 g and then the percent of total weight due to the yolk

sac was determined. Weights were measured after fry had been preserved in formalin for at least six weeks.

### *Monitoring Conditions in the Substrate*

Dissolved oxygen levels and water temperatures in egg pockets were monitored using a PVC pipe (20 cm long x 2.5 cm diameter) placed vertically in the substrate with one end in the egg pocket and the other emerging above the substrate and water surface. The probe of a combination YSI oxygen meter was passed down each pipe to the egg pocket to measure oxygen concentrations. The lower 15 cm of each pipe was perforated with 6 mm holes to allow water flow through the pipe. Apparent velocity (velocity of intragravel flow) was measured by diverting the outflow pipe from each trough into a bucket and measuring the amount of time required to fill a known volume (L/min). Flow measurements were made prior to addition of fine sediment and just prior to completion of the experiment. A continuously recording thermograph was used to monitor maximum daily temperatures in flow returning to the sump tank.

### *Data Analysis*

Four replicates of the twelve treatments (Table 1) were made during this study. However, the sediment intrusion baskets from three troughs that did not receive fine sediment were pulled early during the trial to assure that trout embryos were viable and developing. Data from those three troughs (see Table 1) were excluded from analysis.

Data collected consisted of six variables: amount of fine sediment accumulated upstream, in, and downstream from the egg pocket, fry survival to emergence, mean fry development in each trough, and mean proportion of organic content in the substrate (mean of three samples). Data were analyzed in 12 separate two-way analysis of variance (ANOVA) using the SAS statistical package (SAS Institutes, Inc. 1990). Each of the six response variables were tested for effects of redd versus non-redd substrate surface shape and four added-fine-sediment levels in troughs containing the truncated mix, and effects of truncated versus full-spectrum mix and four added-fine-sedment levels in troughs containing the non-redd substrate surface shape. No troughs

contained the redd shaped substrate with the full-spectrum mix so a full factorial design was not possible. When a significant treatment effect occurred, differences between treatment means were identified using Tukeys multiple comparisons test. Proportions were arcsine-square root transformed to assure normalcy. Significance was set at alpha = 0.05 level.

The relationship between fry survival and amount of accumulated fine sediment was identified by fitting a curve to the plot of proportional survival on proportion of sediment smaller than 0.25 mm in the egg pocket. Young et al. (1991) compared survival of cutthroat trout embryos to 15 substrate measures and found that geometric mean (Dg), as calculated by Lotspeich and Everest (1981), correlated best with survival, and so the relationship between survival and Dg was also identified. Our results were compared to survival values predicted from the model developed by Irving and Bjornn (1984) for rainbow trout embryos in granitic sediment,

$$\text{percent survival} = 113.58 - 10.77(S_{0.85}) - 0.007(S_{9.5})^2 + 0.301(S_{0.85})^2 \qquad [4]$$

where $S_{9.5}$ is the percent of substrate smaller than 9.5 mm and $S_{0.85}$ is the percent of substrate smaller than 0.85 mm diameter. For our calculations, percent of substrate smaller than 0.833 mm was substituted for $S_{0.85}$ in equation 4.

## Results

During the study, three factors were tested: (1) substrate mixture (full-spectrum or truncated), (2) substrate surface shape (redd or non-redd), and (3) amount of fine sediment added (0, 4.5, 9.0, or 18 kg) (Table 1). Of these, the amount of fine sediment added to troughs during the trial had the largest influence on the six response variables (Table 3).

### *Sediment Deposition*

The amount of fine sediment added during the trial had the largest effect on amount of fine sediment (<0.25 mm) found in the troughs upstream, downstream, and in egg

Table 3. Average amounts of fine sediments and geometric mean particle size (Dg) of sediments collected from troughs upstream in, and downstream of egg pockets, percent organics, intragravel flow at completion of test, dissolved oxygen at completion of test, and average percent survival and developmental index (KD) for fry collected from troughs with different substrate mixtures, shape of the substrate surface, and fine sediment addition for trial II. Number of replicates per treatment = 3 or 4, see table 1.

| Substrate mixture | Shape of substrate surface | Fine sediment added (kg) | % Fine sediments <0.25 mm and (Dg) found: up from egg pocket | in egg pocket | down from egg pocket | Percent organics | Final intragravel flow L/min | Final D.O. mg/L | Percent survival | (KD) |
|---|---|---|---|---|---|---|---|---|---|---|
| Truncated | Redd | 0 | 0.6 (17.3) | 0.5 (19.6) | 0.3 (17.9) | 4.6 | 34.2 | 10.3 | 81.5 | 2.27 |
| Truncated | Redd | 4.5 | 2.6 (15.9) | 2.0 (17.6) | 0.6 (18.6) | 3.1 | 38.0 | 10.3 | 77.4 | 2.33 |
| Truncated | Redd | 9.0 | 4.1 (15.0) | 3.5 (16.1) | 0.8 (17.2) | 2.7 | 34.2 | 10.2 | 67.9 | 2.33 |
| Truncated | Redd | 18.0 | 9.9 (10.8) | 5.7 (14.9) | 0.7 (18.9) | 3.7 | 36.8 | 10.3 | 58.9 | 2.56 |
| Truncated | Non-redd | 0 | 0.7 (18.1) | 0.4 (19.7) | 0.3 (17.5) | 3.5 | 34.6 | 10.3 | 75.3 | 2.23 |
| Truncated | Non-redd | 4.5 | 1.4 (18.4) | 2.1 (19.5) | 0.7 (18.3) | 3.6 | 32.9 | 10.3 | 67.5 | 2.33 |
| Truncated | Non-redd | 9.0 | 2.2 (17.4) | 4.2 (15.7) | 0.9 (17.4) | 2.9 | 35.2 | 10.3 | 79.5 | 2.38 |
| Truncated | Non-redd | 18.0 | 5.2 (14.4) | 6.6 (14.6) | 1.1 (18.3) | 3.6 | 33.5 | 10.4 | 47.1 | 2.60 |
| Full-spectrum | Non-redd | 0 | 0.8 (16.0) | 0.7 (16.7) | 0.6 (17.4) | 1.5 | 29.6 | 10.2 | 75.0 | 2.21 |
| Full-spectrum | Non-redd | 4.5 | 1.8 (14.9) | 2.6 (15.3) | 1.3 (14.8) | 1.4 | 26.7 | 10.3 | 71.1 | 2.28 |
| Full-spectrum | Non-redd | 9.0 | 3.3 (13.3) | 4.4 (13.8) | 2.0 (14.9) | 2.0 | 26.3 | 10.3 | 49.3 | 2.26 |
| Full-spectrum | Non-redd | 18.0 | 5.3 (12.0) | 6.8 (12.2) | 2.3 (16.5) | 1.9 | 27.2 | 10.2 | 21.4 | 2.52 |

pockets at the end of the trial. Sediment deposition in troughs was also related to substrate shape, and initial substrate mixture, but none of the interactions were significant. There was generally less fine sediment downstream from the egg pocket than upstream and in the egg pocket (Table 3).

***Upstream from egg pocket.***--A small amount of fine sediment (<0.25 mm = 0.6-0.8% of total substrate weight) was found in the substrate upstream from the egg pocket in troughs where no fine sediment was added during the test (Table 3), but it had no effect on outcome of tests. Fine sediment in troughs where no fine sediment was added came in with recirculated water, despite attempts to prevent contamination.

In the comparison with substrate mixture and sediment added, conducted in troughs with non-redd substrate surface, both main effects were significant; accumulation of fine sediment in troughs with full-spectrum substrate was higher (mean = 2.8% of total substrate weight) than in troughs with the truncated mix (mean = 2.4%), and more fine sediment accumulated as inputs of sediment increased (Table 4). For troughs with either full-spectrum or truncated substrates, fine sediment accumulations were highest in troughs that received 18 kg of fine sediment, intermediate in troughs that received 9 kg, and lowest in troughs that received 4.5 or 0 kg (Tables 3 and 4). The interaction term with substrate mixture and sediment added was not statistically significant ($P = 0.39$), so we did not attempt to determine if any combination of substrate mixture and sediment added caused significantly different accumulations of fine sediment.

In the comparison with substrate shape and sediment added, both main effects had a significant effect on fine sediment accumulated in the upstream end of troughs with the truncated initial substrate mixture (Table 4). Significantly more fine sediment accumulated upstream from the egg pocket (4.3%) in troughs with the redd shape than in troughs with the non-redd substrate shape (2.4%). Addition of 18 kg of fine sediment to troughs resulted in significantly more sediment accumulation than in those troughs that received either 9 or 4.5 kg, and those troughs in turn had more fine sediment than troughs with no sediment added. As in the previous comparison, the interaction between substrate shape and sediment added was not significant ($P = 0.13$).

Table 4. Source of variation, accompanying degrees of freedom (df), probability (P) values from analysis of variance (ANOVA), and results of Tukeys multiple comparison test (when ANOVA $P < 0.05$) for effects of substrate mix (truncated or full-spectrum) or substrate shape (redd or non-redd) and addition of fine sediment <0.25 mm in diameter (0, 4.5, 9.0, or 18.0 kg) on deposition of fine sediment upstream, in, and downstream from the egg pocket, organic content of substrate, embryo to emergent fry survival, and developmental index of emergent fry. Results of subdivided analysis are shown in brackets, when appropriate.

| Source | df | P value | Outcome of Tukeys test |
|---|---|---|---|
| **Fine sediment deposition upstream of egg pocket** | | | |
| ***Substrate mix and fine sediment added*** | | | |
| Substrate mix | 1 | 0.0001 | Full-spectrum > Truncated |
| Added fines | 3 | 0.0001 | 18.0 > 9.0 > 4.5 ns 0 |
| Mix x Fines | 3 | 0.3887 | |
| Error | 22 | | |
| ***Substrate shape and sediment added*** | | | |
| Substrate shape | 1 | 0.0004 | Redd > Non-redd |
| Added fines | 3 | 0.0001 | 18.0 > 9.0 ns 4.5 > 0 |
| Shape x Fines | 3 | 0.1313 | |
| Error | 22 | | |
| **Fine sediment deposition in egg pocket** | | | |
| ***Substrate mix and fine sediment added*** | | | |
| Substrate mix | 1 | 0.0470 | Full-spectrum > Truncated |
| Added fines | 3 | 0.0001 | 18.0 > 9.0 > 4.5 > 0 |
| Mix x Fines | 3 | 0.6705 | |
| Error | 22 | | |
| ***Substrate shape and sediment added*** | | | |
| Substrate shape | 1 | 0.0830 | |
| Added fines | 3 | 0.0001 | 18.0 > 9.0 > 4.5 > 0 |
| Shape x Fines | 3 | 0.5516 | |
| Error | 22 | | |

Table 4. Continued

| Source | df | P value | Outcome of Tukeys test |
|---|---|---|---|
| **Fine sediment deposition downstream of egg pocket** | | | |
| ***Substrate mix and sediment added*** | | | |
| Substrate mix | 1 | 0.0001 | Full-spectrum > Truncated |
| Added fines | 3 | 0.0001 | 18.0 ns 9.0 > 4.5 > 0 |
| Mix x Fines | 3 | 0.0867 | |
| Error | 22 | | |
| ***Substrate shape and sediment added*** | | | |
| Substrate shape | 1 | 0.1400 | |
| Added fines | 3 | 0.0024 | 18.0 ns 9.0 ns 4.5 > 0 |
| Shape x Fines | 3 | 0.4254 | |
| Error | 22 | | |
| **Proportion organic content** | | | |
| ***Substrate mix and sediment added*** | | | |
| Substrate mix | 1 | 0.0026 | Truncated > Full-spectrum |
| Added fines | 3 | 0.8804 | |
| Mix x Fines | 3 | 0.9168 | |
| Error | 22 | | |
| ***Substrate shape and sediment added*** | | | |
| Substrate shape | 1 | 0.4302 | |
| Added fines | 3 | 0.9896 | |
| Shape x Fines | 3 | 0.7552 | |
| Error | 22 | | |
| **Embryo to emergent fry survival** | | | |
| ***Substrate mix and sediment added*** | | | |
| Substrate mix | 1 | 0.0179 | Truncated > Full-spectrum |
| Added fines | 3 | 0.0003 | 0 = 4.5 = 9.0 > 18.0 |
| Mix x Fines | 3 | 0.1703 | |
| Error | 22 | | |

Table 4. Continued

| Source | df | P value | Outcome of Tukeys test |
|---|---|---|---|
| **Embryo to emergent fry survival** | | | |
| ***Substrate shape and sediment added*** | | | |
| Substrate shape | 1 | 0.6501 | |
| Added fines | 3 | 0.0284 | 0 ns 4.5 ns 9.0 > 18.0 |
| Shape x Fines | 3 | 0.5009 | |
| Error | 22 | | |
| **Emergent fry development index** | | | |
| ***Substrate mix and sediment added*** | | | |
| Substrate mix | 1 | 0.7170 | |
| Added fines | 3 | 0.0004 | 18.0 > 9.0 ns 4.5 ns 0 |
| Mix x Fines | 3 | 0.9098 | |
| Error | 22 | | |
| ***Substrate shape and sediment added*** | | | |
| Substrate shape | 1 | 0.2411 | |
| Added fines | 3 | 0.0035 | 18.0 > 9.0 ns 4.5 ns 0 |
| Shape x Fines | 3 | 0.9440 | |
| Error | 22 | | |

***Egg pocket.--***Fine sediment accumulation in the egg pocket was influenced by amount of fine sediment added and by substrate mixture but was not significantly affected by substrate surface shape (Tables 3, 4). In the comparison with substrate mixture and sediment added, conducted in troughs with non-redd substrate surface, both main effects were significant; accumulation of fine sediment in the egg pocket of troughs with full-spectrum substrate was higher (mean = 3.6%) than in troughs with the truncated mix (mean = 3.3%), and fine sediment accumulated was successively higher as fine sediment added increased (Table 4). For troughs with either full-spectrum or

truncated substrates, fine sediment accumulations were successively higher in troughs that received 0, 4.5, 9.0, and 18.0 kg fine sediment (Tables 3 and 4). The interaction term with substrate mixture and sediment added was not statistically significant (P = 0.67).

In the comparison with substrate shape and sediment added, only sediment added had a significant effect on fine sediment accumulated in troughs with the truncated substrate mixture (Table 4). Fine sediments accumulated upstream from the egg pocket in troughs with the redd shape (2.9%) and in troughs with the non-redd substrate shape (3.3%) did not differ significantly (P = 0.08). Fine sediment accumulation in troughs that received 0, 4.5, 9.0, and 18.0 kg fine sediment averaged 0.5, 2.1, 3.9, and 6.2%, and each of these values were significantly different from each other (Table 4). The interaction between substrate shape and sediment added was not significant (P = 0.~~13~~55).

***Downstream from egg pocket.***--Fine sediment accumulation downstream from the egg pocket was generally lower than was found upstream or in the egg pocket and was mainly related to substrate mixture (Tables 3, 4). In the comparison with substrate mixture and sediment added, conducted in troughs with non-redd substrate surface, both main effects were significant; accumulation of fine sediment in troughs with full-spectrum substrate was higher (2.0%) than in troughs with the truncated mix (mean = 0.8%), and more fine sediment accumulated as inputs of sediment increased (Table 4). For troughs with either full-spectrum or truncated substrates, fine sediment accumulations were highest in troughs that received 18 and 9.0 kg of fine sediment, intermediate in troughs that received 4.5 kg, and lowest in troughs that received 0 kg (Tables 3 and 4). The interaction term with substrate mixture and sediment added was not statistically significant (P = 0.09).

In the comparison with substrate shape and sediment added, only sediment added had a significant effect on fine sediment accumulated in troughs with the truncated substrate mixture (Table 4). Fine sediment that accumulated upstream from the egg pocket in troughs with the redd shape (0.6%) and with the non-redd substrate shape

(0.8%) did not differ significantly. Adding 18.0, 9.0, and 4.5 kg of fine sediment to troughs resulted in significantly more sediment accumulation than in troughs that received no sediment. The interaction between substrate shape and sediment added was not significant (P = 0.43).

### *Organic Content*

Organic content of substrate was higher in troughs containing the truncated mix than in troughs containing the full-spectrum mix, but was not related to amount of fine sediment added to troughs during the trial, or to substrate shape. In the comparison with substrate mixture and sediment added, conducted in troughs with non-redd substrate, organic content of the substrate was higher in troughs with the truncated mix (mean = 3.4%) than in troughs with the full-spectrum mix (mean = 1.7%), but there was no effect related to amount of fine sediment added to those troughs (Table 4). In the comparison with substrate shape and sediment added, organic content of the substrate did not differ significantly between troughs with and without the redd-shaped substrate, or between troughs that received different amounts of fine sediment (Table 4).

### *Fry Survival*

Survival from newly fertilized egg to emergent fry was lower at the highest sediment loading rate and with the full-spectrum mix of substrate, but substrate shape had no effect on survival (Tables 3, 4). Survival of embryos that developed in the Heath trays averaged 71.1%. In the comparison with substrate mixture and sediment added, conducted in troughs with non-redd substrate surface, both main effects were significant; fry survival in troughs with the full-spectrum substrate was lower (54.2%) than in troughs with the truncated mix (mean = 67.4%) (Table 4). For troughs with either full-spectrum or truncated substrates, fry survival was significantly lower in troughs that received 18 kg of fine sediment than in troughs that received 0, 4.5, and 9.0 kg fine sediment (Tables 3 and 4). The interaction term with substrate mixture and sediment added was not statistically significant (P = 0.17).

In the comparison with substrate shape and sediment added, only sediment added had a significant effect on fine sediment accumulated in troughs with the truncated initial substrate mixture (Table 4). Fry survival in troughs with the redd shape (71.6%) and with the non-redd substrate shape (67.4%) did not differ significantly. Survival was significantly lower in troughs that received 18.0 kg added sediment than in troughs that received 0. 4.5, and 9.0 kg added sediment. The interaction between substrate shape and sediment added was not significant ($P = 0.50$).

Intragravel flow, measured at the outflow of each trough prior to the completion of study was significantly higher from troughs containing the truncated substrate mix (mean = 33.8 L/min) than from troughs containing the full-spectrum mix (mean = 27.4 L/min, $P = 0.0026$), but there was no difference in flows based on substrate surface shape or amount of fine sediment added to troughs. Dissolved oxygen levels in troughs were 10.2-10.4 mg/L prior to completion of the test and did not vary significantly between troughs.

The relations between survival and proportion of fine sediment in the egg pocket was curvilinear and was best represented by the quadratic equation,

$$\text{proportional survival} = 0.763 + 1.0596(P_{0.25}) + -97.0156(P_{0.25})^2 \qquad [5]$$

where $P_{0.25}$ is the proportion of sediment smaller than 0.25 mm diameter in the egg pocket (Figure 2). The $R^2$ value for equation 5 was 0.5296. The best-fit curve between proportional survival and Dg was

$$\text{proportional survival} = -2.9588 + 0.3988(Dg) + -0.0107(Dg)^2 \qquad [6]$$

and had an $R^2$ value of 0.5717 (Figure 2).

### *Development Index*

Development index for emergent trout fry did not vary by substrate surface shape or substrate mix, but there was a difference between sediment loads (Tables 3, 4).

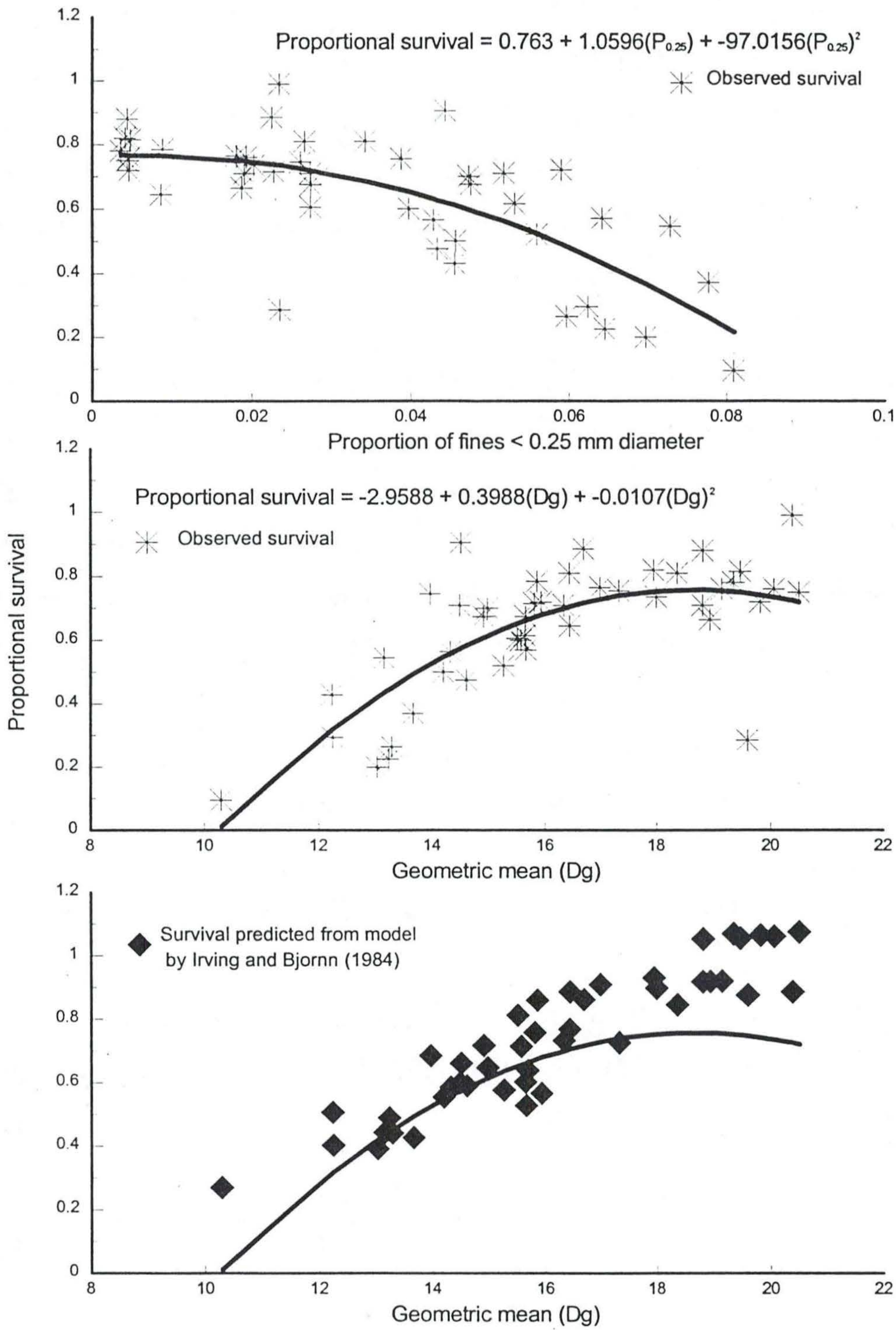


Figure 2. Proportional survival-to-emergence observed for rainbow trout embryos in 48 experimental troughs, plotted against proportion of sediments smaller than 0.25 mm (top) and geometric mean (middle) in the egg pocket. Survival predicted from model developed by Irving and Bjornn (1984) for rainbow trout embryos in granitic sediment plotted against geometric mean of sediment in the egg pocket with the curve from this study for comparison (bottom).

However, percent of body weight from the yolk sac for emergent fry averaged 33.2% and did not vary by substrate surface shape, substrate mixture, or amount of sediment added during the trial.

Fry that developed in the Heath trays had an average KD value of 2.11. Developmental index for fry in troughs containing the truncated substrate mix, averaged 2.37 in troughs with the redd substrate shape and 2.39 in troughs with the non-redd substrate shape, and these values did not differ significantly (Table 4). Likewise, fry collected from troughs with the full-spectrum substrate mix (mean = 2.32) had similar condition factors as fry collected from troughs that contained the truncated mix (mean = 2.39) (Table 4). In both analyses, developmental index values for fry collected from troughs that received 18.0 kg of fine sediment (mean = 2.60) were significantly higher than those of fry collected from troughs that received 0, 4.5, and 9.0 kg of added fine sediment (means = 2.24, 2.31, and 2.32) (Table 4), and no other comparisons were significant.

## Discussion

Much of the research on effects of fine sediment on survival of salmonid embryos has focused on fine sand to small gravel-sized sediment because of an interest in evaluating effects of logging and roads in areas with granitic soils, such as the Idaho Batholith (Megahan and Kidd 1972). Research on granitic sediment began with events such as occurred in the South Fork Salmon River, Idaho, in the 1960's, when erosion related primarily to logging roads coupled with rain-on-snow storms filled pools and covered spawning areas with sand (Everest et al. 1987; Platts et al. 1989). The effects of silt and clay-sized particles, that erode from sedimentary and metamorphic deposits, on embryo survival has not been studied extensively (e.g. Magee et al. 1996).

In this study we investigated the effects of fine sediment (<0.25 mm in diameter) on the survival and development of trout embryos. We found that survival decreased and development of embryos was retarded when relatively small percentages of fine sediment accumulated in the simulated redds. In studies with coarse sand sediment (2-6 mm or <6.4 mm diameter), significant declines in salmonid embryo-to-fry survival

occurred when the larger fine sediment made up 20-30% of the sediment mixture (McCuddin 1977; Wetzel and MacCrimmon 1983; Irving and Bjornn 1984; Shepard et al. 1985). With fine sand (0.5-2.0 mm diameter), coho salmon and steelhead embryo-to-fry survival significantly declined when percent fines in the sediment exceeded 10% (Phillips at al. 1975). Peterson and Metcalf (1981) also found that survival of Atlantic salmon embryos was lower in fine than course-sized sands. During our study, mean embryo-to-fry survival decreased gradually when fine sediments (<0,25 mm) made up 1-4 % of the substrate by weight, and decreased rapidly when fine sediment in the egg pocket exceeded about 5.0% (Figure 2). 0.2

Irving and Bjornn (1984) developed a model that related survival-to-emergence for rainbow trout to the percent of substrate smaller than 9.5 mm and smaller than 0.85 mm diameter. Predictions of survival based on their model, using size fractions from this study smaller than 9.5 mm and smaller than 0.833 mm diameter, were on average 9.6 percentage points higher than fry survival we observed in the troughs, and 10.6 percentage points higher than predicted from equation 6 (Figure 2).

Fine sediments in streambed substrates can be detrimental to embryo survival if they reduce intragravel water exchange, reduce dissolved oxygen available to embryos, impede dilution of metabolic wastes, and restrict movements of alevins (Bjornn and Reiser 1991). In our test, intragravel flow and dissolved oxygen in the substrate of the troughs did not change significantly with the addition of fine sediments. The decrease in survival of embryos with increased amounts of fine sediment (Figure 2) was probably not due to lack of dissolved oxygen, leaving entrapment within the substrate as a possible cause of the mortality. We could not evaluate the likelihood of entrapment of fry because we continued the test well past the peak period of emergence to give all fry a chance to emerge, thus dead fry were not likely to be found during substrate sampling and removal of the substrate from the troughs at the end of the test.

Cooper (1965) demonstrated how the redd structure may increase intragravel flows through egg pockets. In a review of sediment-embryo survival studies, Chapman (1988) was critical of sediment-embyro survival studies, especially those performed in

laboratories, because he believed the researchers had not considered effects that redd structure had on fine sediment accumulations in natural redds and effects of shape of the substrate surface on embryo survival. In this study, we shaped the surface of the substrate in some troughs similar to that of a natural redd, but found that embryo-to-fry survival was not affected by shape of the substrate surface in the troughs. More fine sediment accumulated upstream from the egg pocket in troughs with redd shape than in those with non-redd shape, but there was no difference in deposition of fine sediment in the egg pocket or downstream from the egg pocket in troughs with the two surface shapes. Intragravel flows and dissolved oxygen concentrations were not affected by shape of the substrate surface. Admittedly, we could not emulate fully a natural redd in the troughs we used, and perhaps some of the characteristics we were unable to emulate were those that affect survival of embryos. For experimental design reasons, we allowed water to flow over the substrate surface in troughs only at the time fry were emerging, thus full effects of redd shape on hydraulic conditions that affect embryos within the troughs during incubation may not have existed. Initial substrates used in our study were pre-selected mixtures, whereas the amount of fine sediment in substrates of natural redds can vary from relatively low levels in the egg pocket to higher amounts in undisturbed gravel at the margins of a redd. When we created egg pockets in troughs with both redd and non-redd shaped substrates, we shut down the flow to minimize redistribution of fines, and the embryos were covered with surrounding substrate. Substrates in troughs differed by surface shape, initial mixture (full and truncated), and accumulation of sediment from the fine sediments that were added soon after the embryos were placed in the troughs.

Female salmonids remove fine sediment from egg pockets and from the surrounding area during redd construction, which may improve embryo incubation conditions (Chapman 1988; Young et al. 1989). We found that more fine sediment accumulated and embryo-to-emergent fry survival was lower in troughs with the full-spectrum substrate mix than in troughs with the truncated mixture (particles <4.75 mm removed). The full-spectrum substrate retained more of the fine sediment added to the troughs during incubation than the truncated substrate. Cooper (1965) found that gravel

composition can affect water flow through the substrate, and thus affect deposition of fine sediment. Substrate containing small gravel could retain more sediment than substrate without the small gravel, as discussed by Chapman (1988). Koski (1975), however, reported that with high proportions of sand (0.105-3.327 mm) in stream substrate, retention of silt and clay particles declined because interstitial spaces were already filled with sand.

The appropriate measures to assess quality of substrate used for salmonid spawning and incubation has been discussed by many investigators. Tappel and Bjornn (1983) and Irving and Bjornn (1984) suggested using the percent fine sediment smaller than 9.5 mm and 0.85 mm, and they developed a model with those two variables to predict survival to emergence for rainbow trout, cutthroat trout, kokanee, steelhead, and chinook salmon embryos. In reexamining data presented by Tappel and Bjornn (1983) and Koski (1966), Chapman (1988) concluded that embryo survival had the highest correlation with the fredle index, Fi. Young et al. (1990), however, disagreed with Chapman's analysis, and concluded that the fredle index and geometric mean Dg were equivalent in usefulness to predict survival potential from a given substrate composition. Young et al. (1991) assessed 15 different sediment measures in their relation to cutthroat trout survival in the laboratory and to spawning areas in the field. They concluded that geometric mean had the highest correlation with survival of cutthroat trout embryos in laboratory aquaria, but percent of particles smaller than 0.85 mm diameter was the best measure of known changes that occurred in cutthroat trout spawning areas in streams. We found curvilinear relations between embryo survival and proportion of sediments smaller than 0.25 mm, and between survival and geometric mean (Dg). Survival estimates calculated using Irving and Bjornn's (1984) model for rainbow trout embryos in granitic substrate were about ten percentage points higher than what we observed during this study. The silt and clay content of sediment used by Irving and Bjornn was not determined, but was probably low considering the source of the sediments (alluvial deposit from central Idaho). This supports the premise that results from these types of studies should only be applied to watersheds that contain comparable sediment. There may not be a single measure of fine sediments

that can be used universally to predict survival or assess quality of stream beds used for spawning. Sowden and Power (1985) suggested that substrate composition alone may not be sufficient to predict survival, but that groundwater flows and dissolved oxygen levels should also be considered. In our study, the latter two factors were not related to embryo survival. Everest et al. (1987) suggested that the appropriate variable(s) to describe stream substrates will vary with location, geology, and species in question.

What then is the applicability of results of laboratory studies such as those reported here and cited? We found that relatively small amounts of fine sediments <0.25 mm that accumulated in the egg pocket in the troughs after a short period of sediment addition caused high mortality of rainbow trout as embryos or alevins. We were unable to completely mimic in the lab all conditions that might exist in a stream used for spawning. Furthermore, we doubt we could accurately measure embryo survival and assess substrate conditions in redds in natural streams to obtain similar results; there are too many uncontrollable variables in natural streams. If nothing more, we provided evidence that embryo survival can vary depending on the size and amount of fine sediments in the egg pocket; 6-7% of the <0.25 mm fines reduced survival from 80% to 20%, whereas with fine granitic sediments (<6.35 mm with few fines smaller that 0.25 mm), fines had to make up more than 20% of the substrate to reduce survival (Irving and Bjornn 1984). In our view, both field and laboratory studies are necessary to develop a complete understanding of the dynamics of sediment transport and deposition in streams and its effects on salmonid spawning and incubation. A knowledge of substrate conditions after spawning and incubation, preferably in redds, is required to determine if results from the various laboratory studies can be applied to natural streams of interest.

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